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DEPOSITIONAL PROCESSES AND STRATIGRAPHIC EVOLUTION OF THE CAMPANIAN DELTAIC SYSTEM OF LA ANITA FORMATION, AUSTRAL-MAGALLANES BASIN, PATAGONIA, ARGENTINA

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ABSTRACT

Coastal depositional systems are commonly classified in terms of the relative interaction of wave, tide and fluvial processes. The La Anita Formation represents the opportunity to study and better understand coastal sedimentary systems. It is a poorly studied prograding siliciclastic deltaic-coastal wedge accumulated in the Campanian during the foreland stage of the Austral-Magallanes Basin. A detailed depositional process-based facies analysis have allowed the definition of 13 sedimentary facies and 9 facies associations for the La Anita Formation, ranging from prodelta to interdistributary delta-channel deposits. According to the spatial distribution of these facies associations, the La Anita Formation was divided into two informal units bounded by a regional erosion surface. The lower unit shows abundant hummocky cross-bedded and bioturbated sandstones, coarsening-upward trends and mainly aggradational to progradational vertical stacking pattern, and it was interpreted as a wave-dominated fluvial-influenced delta. The upper unit is characterized by unidirectional dune cross-bedding, coarsening-upward trend and a progradational vertical stacking pattern, and was interpreted as a fluvio-dominated delta with no evidence of tide or wave influence. These two units represent two genetically unrelated depositional sequences bounded by a regional erosion surface, which is interpreted as a sequence boundary triggered by a relative sea-level fall. The lower unit is part of a progradational highstand systems tract which involves the underlying deep-marine Alta Vista Formation. The upper unit deposits reflect a complete relative sea-level cycle which includes an undifferentiated lowstand and transgressive systems tracts and, toward the top, highstand systems tract.

INTRODUCTION

Coastal depositional environments are extremely dynamic, showing multiple coexisting depositional systems evolving through time. The main factors controlling these systems are: i) the relative dominance of fluvial, wave and tide energies, ii) the sediment supply, iii) the basin and shoreline morphology and iv) the relative sea-level changes (Galloway, 1975; Dalrymple *et al*., 1992; Boyd *et al*., 1992; Ainsworth *et al.*, 2011). The coastal depositional systems accumulated in the initial phase of the foreland stage of the Austral-Magallanes Basin (AMB), during the Upper Cretaceous, are poorly-studied and represent a great opportunity to continue testing hypotheses about coastal depositional systems.

The Upper Cretaceous shallow-marine and coastal depositional systems of the AMB have not received the same amount of attention as deep-marine and continental depositional systems in recent studies (Richiano *et al.*, 2012, 2013, 2015; Varela *et al.*, 2012a,b, 2013, 2018, Varela, 2015; Malkowski *et al.*, 2015; Sickmann *et al.*, 2018). The La Anita Formation (LAF) deposits have been interpreted in some regional and stratigraphic studies as accumulated in shallow-marine to coastal environments (Arbe, 1986, 2002; Manassero, 1988; Macellari *et al.*, 1989). However, detailed sedimentological, ichnological and paleoenvironmental characterization of these deposits are needed in order to constrain depositional processes, water-salinity conditions and definition of depositional systems. The Campanian LAF deposits provide excellent exposures that allow a better understanding of coastal and shallow-marine depositional systems and to unravel the evolution of the depositional history of the AMB. The specific goals of this contribution are: i) to define the sedimentary paleoenvironments where LAF accumulated and ii) to recognize stratigraphic variations in the relative roles of depositional processes.

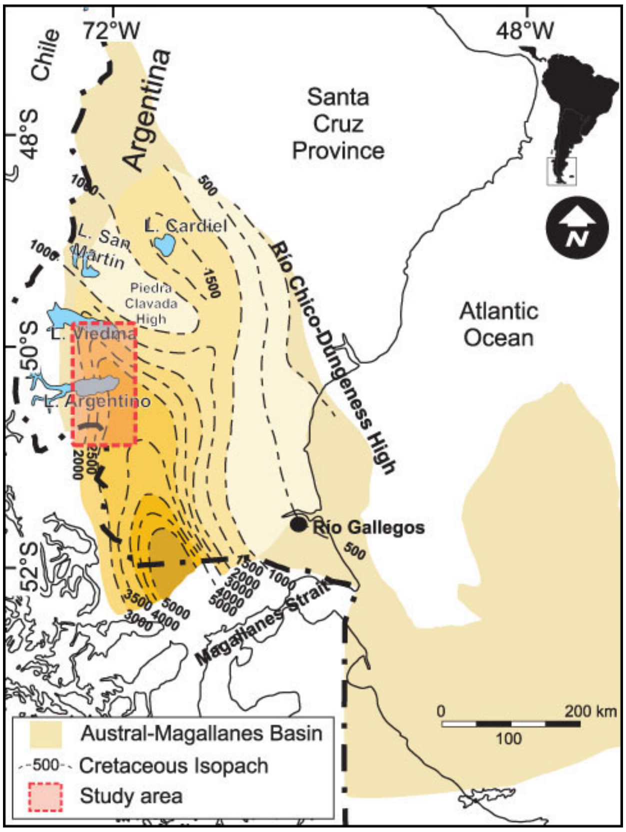


Figure 1. Location map of the Austral-Magallanes Basin. Isopachs obtained from seismic data (Marinelli, 1998) show thickness and distribution of Cretaceous deposits. The red box shows the location of the study area.

GEOLOGICAL SETTING

The AMB is located at the south-western part of the South American Plate, in the southern end of Argentina and Chile (Fig. 1). It presents a north-south elongated shape with a marked widening toward the south (Fig. 1). The basin is bounded by the Río Chico-Dungeness High to the east, by the Patagonian-Fueguian Andes to the west and by a transform fault to the south. The tectonic history of the AMB consist of three main tectonic stages (Biddle *et al.*, 1986; Arbe, 1986, 2002; Robbiano *et al.*, 1996; Kraemer *et al.*, 2002; Peroni *et al.*, 2002; Rodriguez and Miller, 2005; Varela *et al.*, 2012a; Ghiglione *et al.*, 2015; Malkowski *et al.*, 2015; Sickmann *et al.*, 2018): i) an initial extensional stage, related to the break-up of Gondwana during the Early to Middle Jurassic (Pankhurst *et al.*, 2000), represented by volcanic, volcaniclastic and siliciclastic deposits of El Quemado Complex (Fig. 2; Biddle *et al.*, 1986); ii) a thermal subsidence stage (Thitonian – Albian) associated with the transgressive deposition of the shallow- and deep-marine Springhill and Río Mayer formations, respectively (Fig. 2) (Biddle *et al.*, 1986; Arbe, 1986, 2002; Rodriguez and Miller, 2005; Richiano *et al.*, 2012, 2013, 2015); and finally iii) the onset of a foreland basin stage due to a compressional regime that took place in the Middle Cretaceous (*ca* 100 Ma) (Fig. 2; Fildani *et al.*, 2003; Fosdick *et al.*, 2011; Varela *et al.*, 2012a, Ghiglione *et al.*, 2015; Malkowski *et al.*, 2015).

The La Anita Formation

The La Anita Formation (Bianchi, 1967) is part of a prograding siliciclastic wedge accumulated during the foreland stage of the AMB. The age of the LAF was restricted to the Campanian based on the presence of ammonites (Riccardi and Rolleri, 1980, Riccardi, 1983; Kraemer and Riccardi, 1997) and by recently published detrital zircon maximum depositional ages (Sickmann *et al.*, 2018). The LAF overlies dark fine-grained deep-marine deposits of the Alta Vista Formation and it is overlaid by coarse-grained continental deposits of the Cerro Fortaleza and La Irene formations (Fig. 2). The LAF it is mainly characterized by sandstones and pebbly sandstones, with subordinate mudstones and heterolithic deposits (Feruglio, 1938, 1944, 1949; Leanza, 1972; Manassero, 1988; Macellari *et al.*, 1989; Moyano Paz *et al.*, 2016, 2018).

STUDY AREA AND METHODS

The study area corresponds to the Lago Argentino region, located in the southwestern part of the Santa Cruz province, Patagonia, Argentina (Figs. 1, 3). The Lago Argentino region shows complete exposures of the Mesozoic sedimentary infill of the basin. The LAF exposures are restricted to this area. Detailed sedimentary logs of the LAF exposures were measured and described for eight localities (Figs. 3, 4). Thirteen sedimentary facies (SFs) were defined based on thickness, grain-size, sorting, sedimentary structure and bioturbation index (BI; Reineck and Singh, 1980; Taylor and Goldring, 1993), which allowed the identification of depositional processes (Table 1). Nine facies associations (FAs) were identified by the recurrent appearance of groups of SFs, paleocurrent directions, stratal architecture, bounding surfaces and trace-fossil assamblages (Table 2). Paleocurrent directions were measured in dune and ripple cross-bedding structures. The lateral and vertical distribution of the FAs were constrained in order to define the depositional systems in which the LAF accumulated. Correlation of the measured sections was done by walking out or by visually tracing the first appearance of a clean coal bed using high-resolution outcrop photopanels. Also, key stratigraphic surfaces where recognized and followed in order to constrain a sequence stratigraphic framework.

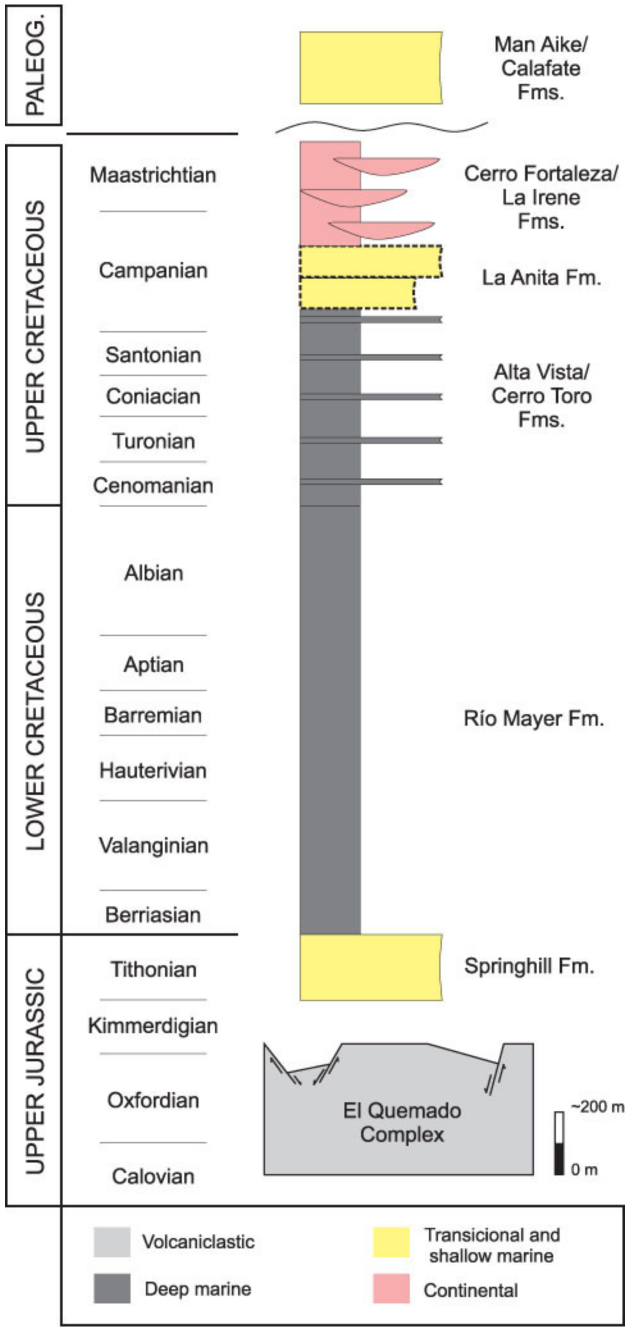


Figure 2. Stratigraphic scheme of the sedimentary infill for the Austral-Magallanes Basin in the Lago Argentino region (modified from Ghiglione *et al.*, 2014; Sickmann *et al.*, 2018).

FACIES ASSOCIATIONS

Facies Association 1: wave-dominated prodelta

Description: This FA transitionally overlies the deep-marine fine-grained sediments of the Alta Vista Formation and it is overlain by sandstones of the wave-dominated distal delta front sandstones (FA2). It is also recorded above the sediments of FA2 through flooding surfaces. FA1 forms tabular bodies up to 5 m thick and at least 400 m of lateral continuity. They consist of interbedded black mudstones, heterolithic deposits and very fine- to fine-grained sandstones with coarsening and thickening upward trends (Fig. 5a). Mudstones facies are typically parallel-laminated

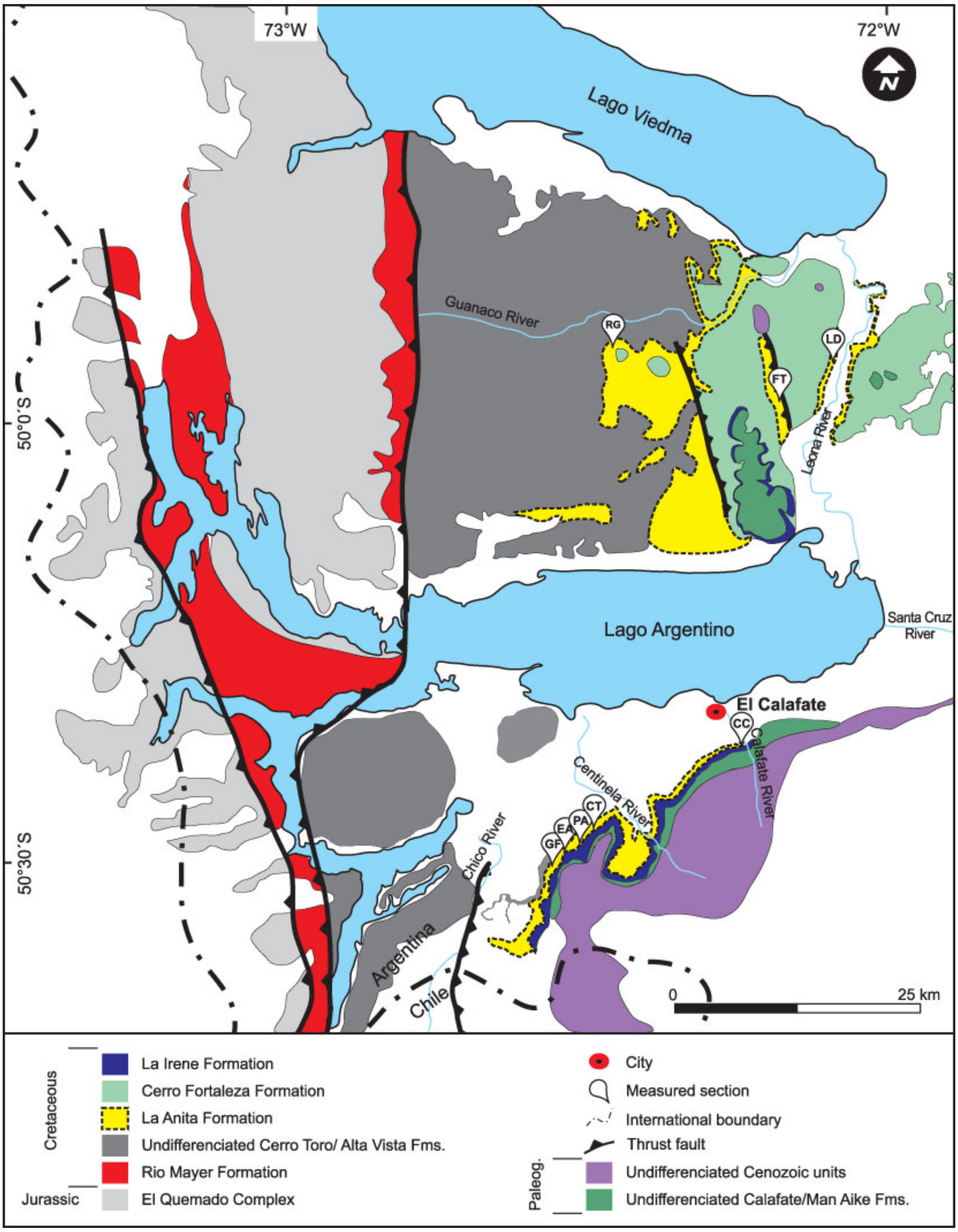


Figure 3. Geological map of the study area showing the distribution of stratigraphic units of the Austral-Magallanes Basin (modified from Kraemer and Riccardi, 1997; Ghiglione *et al*., 2014). Measured section names: RG = Río Guanaco; FT = Filo del Turbio; LD = Luz Divina; GF = Galpón de Freile; EA = Estancia Anita; PA = Paredón; CT = Campo Tropilla; and CC = Cerro Calafate.

or structureless, whereas heterolithic deposits show wavy and rare flaser laminations. Sandstones facies show hummocky cross-stratification (HCS) (Fig. 5b) and parallel-lamination with sparse pebble-sized clasts. FA1 shows low abundance and low diversity of biogenic structures (BI 0 - 3) in mudstones, heterolithic and sandstones facies, but highly bioturbated sandstones (BI 4 - 5) were also observed. In the sandstone layers, the trace-fossil suite consists of burrows with coated walls attributed to *Ophiomorpha* isp., vertical and sub-horizontal "U"-shaped burrows with or without spreiten attributed to *Diplocraterion* isp., *Rhizocorallium* isp., and *Arenicolites* isp. and simple vertical and horizontal burrows attributed to *Skolithos* isp. The fine-grained layers show *Planolites* isp. as the identified traces. Vegetal remains, such as leaves, wood fragments and carbonaceous material are abundant (Fig. 5c).

Interpretation: FA1 reflects alternations of settling of

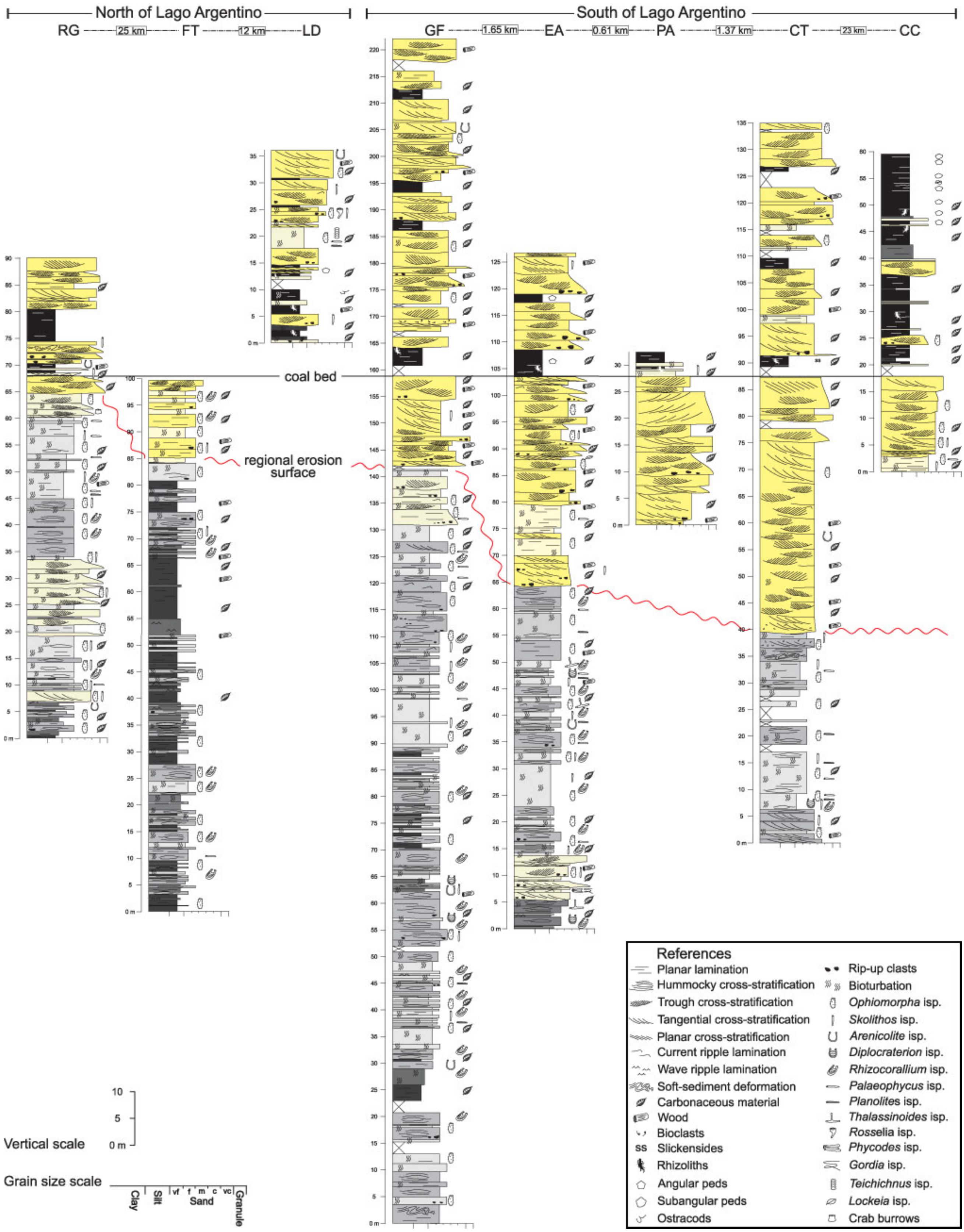


Figure 4. Detailed sedimentologic logs of the La Anita Formation at the Lago Argentino region. For location of the sections see Fig. 3.

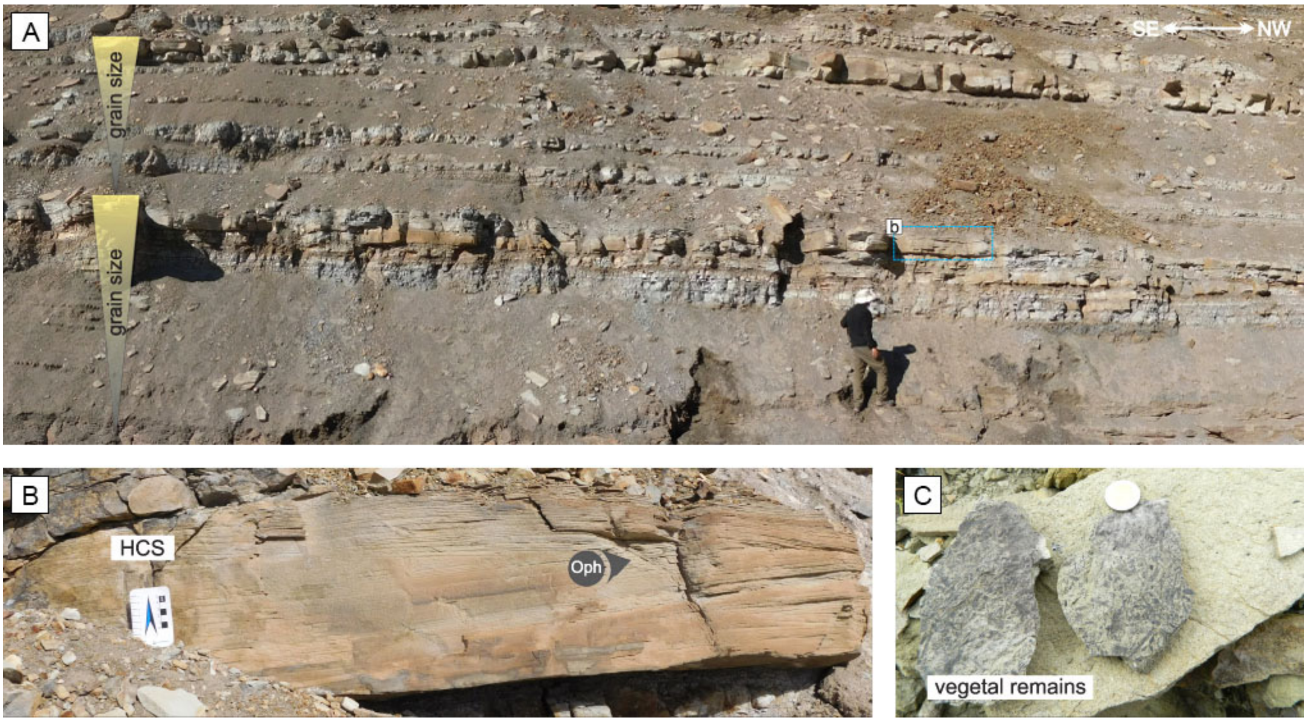


Figure 5. a) Outcrop panel of Facies Association 1 showing tabular geometry of the beds and coarsening upward trends. **b)** Detail of hummocky cross-stratified (HCS) sandstone facies with *Ophiomorpha* isp. (Oph) burrows. **c)** Detail bedding plane view of abundant carbonaceous remains within HCS sandstones facies.

fine-grained sediments during fair-weather conditions or in the final phase of storm events and deposition of coarser-grained sediments by combined unidirectional and oscillatory flows during storm events. The storm-generated sandstones layers show a trace-fossil suite attributed to the *Skolithos* ichnofacies while the fair-weather fine-grained layers show a suite related to the *Cruziana* ichnofacies. The general low BIs suggest a brackish to marine environment. Low BIs and the abundance of HCS beds reflect high storm events frequency with limited time available for the deposition of fair weather beds (*cf*. Bann *et al*., 2008). The presence of sparse pebble-sized clasts and abundant vegetal material reflects input from local rivers (Bhattacharya, 2006; Bann *et al*., 2008). The low diversity of traces within fair-weather fine-grained layers could also be reflecting fluvial influence. FA1 suggests deposition in an offshore-transition bathymetry, between the storm and the fair-weather wave base (Dott and Bourgeois, 1982; Myrow and Southard, 1996; Dumas and Arnott, 2006; Eide *et al*., 2015). However, due to the presence of active fluvial-current effects, FA1 is interpreted as deposited in a wave-dominated prodelta.

Facies Association 2: wave-dominated distal delta front

Description: This FA grades vertically from sediments of FA1 or from the Alta Vista Formation shales. It also overlies sediments of FA3 and FA4 through flooding surfaces. FA2 grades upward into sediments of FA3 or it is incised by channel-shaped bodies of FA4 and FA5. It forms low-angle clinothems (4° - 7°) composed of very fine- to fine-grained sandstones with coarsening-upward trends (Fig. 6a) up to ~15 m thick. In some cases, they amalgamate and generate composite units up to 45 m thick and few hundred meters of lateral continuity. FA2 shows interbedded highly bioturbated (BI 4 - 6) and HCS and parallel-laminated sandstones facies (Fig. 6a-b) with lower BI (BI 1 – 3). Stratified sandstones facies are frequently present as strongly amalgamated sandbodies up to 10 m thick and more than 100 m of lateral continuity with internal erosional surfaces (Fig. 6a), mudstone rip-up clasts and soft-sediment deformation structures facies. The trace-fossil suite is composed mainly of burrows with coated walls attributed to *Ophiomorpha* isp. (Fig. 6c) and

SF	LITHOLOGY	SEDIMENTARY STRUCTURES	SORTING	THICKNESS (cm)	ORGANIC COMPONENTS	BI	DEPOSITIONAL PROCESSES
1	Mudstones	Parallel-lamination, structureless	Well	5 to 600	Leaves and wood fragments	0 - 1	Settling of suspended fine-grained sediments
2	Mudstones	Structureless, slickensides, peds, rhizoliths	Well	20 to 150	Leaves fragments and carbonaceous material	0 - 1	Settling of suspended fine-grained sediments, soil development
3	Heterolithic	Flaser and wavy laminations	Moderate to poor	5 to 50	Carbonaceous drapes	0 - 2	Migration and aggradation of current and oscillation ripples with periods of settling of suspended fine-grained sediments
4	Fine- to very coarse-grained sandstones	Trough cross-bedding, fining-upward trends, mud rip-up clasts	Well to poor	15 to 100	Leaves, wood fragments and phytodetritus drapes	0 - 2	Migration of 3D sandy dunes
5	Fine- to coarse-grained sandstones	Planar cross-bedding, fining-upward trends, mud rip-up clasts	Moderate to poor	20 to 100	Leaves, wood fragments and carbonaceous remains	0 - 1	Migration of 2D sandy dunes
6	Very fine- to fine-grained sandstones	Hummocky cross-bedding, mud rip-up clasts	Well	10 to 50	Leave and wood fragments, phytodetritus drapes	0 - 4	Aggradation and migration of combined-flow structures developed during storm events
7	Fine- to medium-grained sandstones	Trough ripple cross-lamination, asymmetric ripples	Well	10 to 30	Carbonaceous drapes	0 - 1	Migration of 3D current ripples
8	Very fine- to fine-grained sandstones, muddy sandstones	Wavy lamination, symmetric ripples	Well to moderate	20 to 50	-	0 - 1	Aggradation of oscillation ripples
9	Very fine- to coarse-grained sandstones	Parallel-lamination, mud rip-up clasts, fining-upward trends	Well to poor	5 to 120	Leaves fragments	0 - 2	Unidirectional current, upper flow regime flat-bedding
10	Fine- to very coarse-grained sandstones, fine-grained conglomerates	Structureless, mud rip-up clasts	Moderate to poor	50 to 100	-	0 - 1	Quick deceleration of sediment concentrated gravity- currents
11	Hetherolithic deposits, very fine- to fine-grained sandstones	Structureless	Poor	10 to 200	Leaves, wood fragments and carbonaceous remains	4 - 6	Mainly tractive deposition, subordinate settling from suspension, obliterated substrate by intense organisms reworking
12	Fine- to medium-grained sandstones	Soft-sediment deformation	Well to moderate	60 to 150	-	0	Plastic deformation in partially liquefied substrate
13	Pebbly-sandstones, fine grained conglomerates	Trough cross-bedding, fining-upward trends, mud rip-up clasts	Poor to moderate	70	Leaves, wood fragments and phytodetritus drapes	0 - 1	Migration of 3D sandy-gravel, and gravelly dunes

Table 1. Characteristics of the Sedimentary Facies (SFs) identified for La Anita Formation.

horizontal spreiten "U"-shaped burrows attributed to *Rhizocorallium* isp., although *Thallassinoides* isp. galleries, vertical spreiten "U"-shaped burrows attributed to *Diplocraterion* isp., and simple vertical and horizontal burrows attributed to *Skolithos* isp., *Planolites* isp. and *Palaeophycus* isp. are also present.

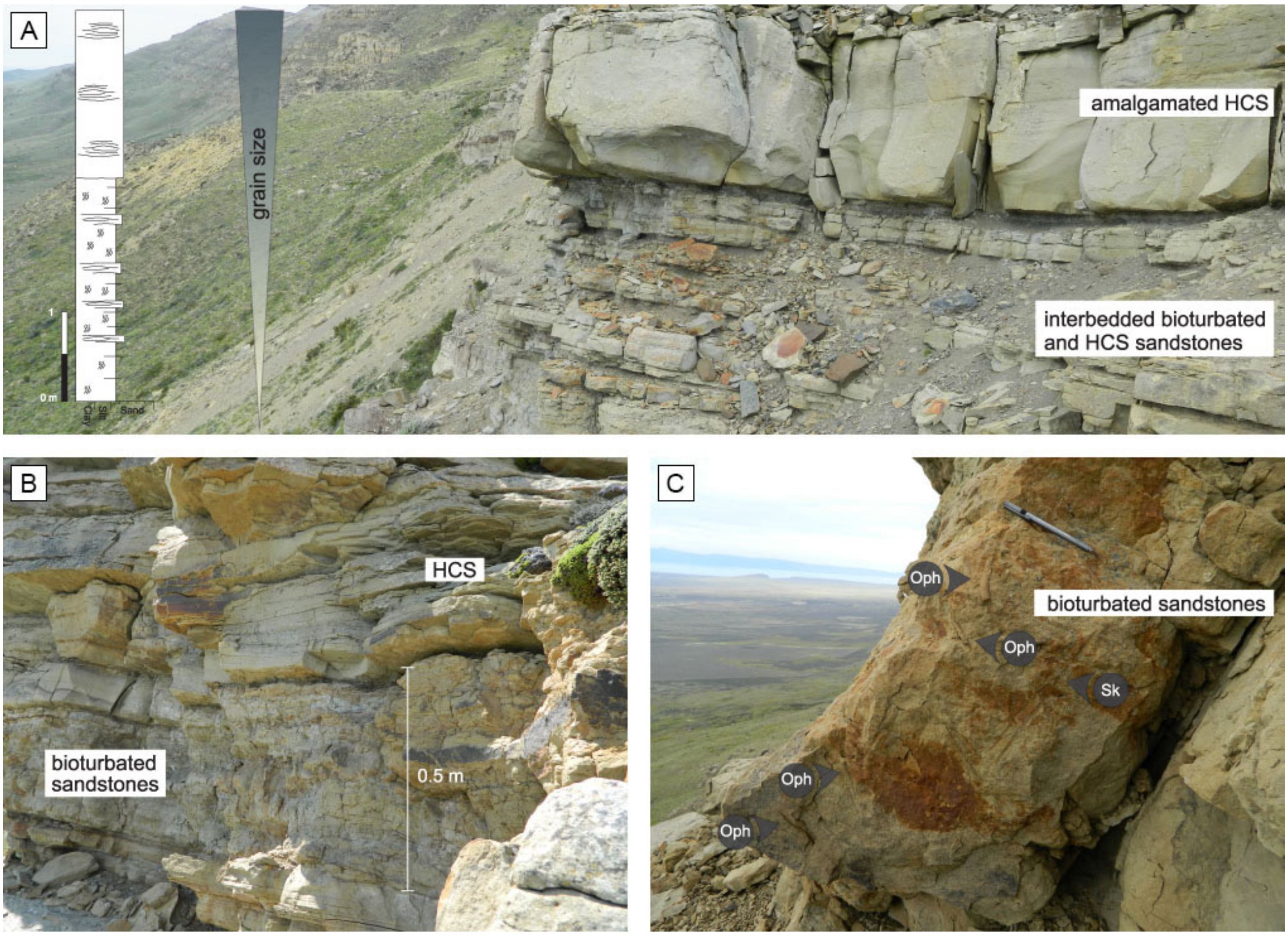


Figure 6. Representative outcrop photographs of Facies Association 2. **a)** Coarsening-upward trend showing interbedding of hummocky cross-stratified (HCS) beds and highly bioturbated sandstones, and amalgamated HCS on top (view to the southeast). **b)** Detail of bioturbated and HCS sandstone deposits. **c)** Detail of abundant *Ophiomorpha* isp. burrows in bioturbated sandstone facies.

Vegetal remains, such as leaves, wood fragments and carbonaceous material are abundant.

Interpretation: HCS and parallel-laminated sandstones reflect friction-dominated, combined- and oscillatory-flow generated structures formed during storm events (Myrow and Southard, 1996; Dumas and Arnott, 2006), whereas bioturbated beds are the result of the reworking of those storm-sheets by organisms during fair-weather conditions (Bann *et al*., 2008; Buatois and Mángano, 2011). Strongly amalgamated storm-generated sandbodies indicate high frequency of relax-currents generated after storm events (post-storm flows) that eroded bedforms generated under fair-weather conditions (Dott and Bourgeos, 1982; Isla *et al*., 2018). The trace-fossil suite is attributed to a stressed expression of proximal *Cruziana* to distal *Skolithos* (MacEachern *et al*., 2007; Bann *et al*., 2008; Buatois and Mángano, 2011), developed in a brackish to marine environment with high recurrence of storm events. The presence of sparse pebble-size clasts and vegetal remains reflect input from local rivers (Bhattacharya, 2006; Bann *et al*., 2008). FA2 suggests deposition in a zone above the fair-weather wave base (Clifton, 2006), however, the presence of fluvial-currents effect suggest deposition in a wave-dominated distal delta front environment.

Facies Association 3: wave-dominated proximal delta front

Description: FA3 forms tabular, horizontal to gently inclined (3° - 5°) bodies that grades vertically from the sediments of the wave-dominated distal delta front (FA2) into gray-colored, well-sorted, fine- to medium-grained sandstones (Fig. 7). It is overlaid by channelized incisions of FA4 or by FA2 deposits. FA3 is up to 5 m thick and tens of meters lateral continuity. It is composed of trough cross-bedding sets up to 0.4 m thick (Fig. 7). Parallel-laminated and asymmetric ripple cross-laminated facies with sparse pebble-sized clasts are common. The cross-beds are oriented toward the northeast (Table 2). This FA is typically unburrowed (BI 0 - 2), however, a scattered trace-fossil suite composed of vertical burrows attributed to *Ophiomorpha* isp. and *Skolithos* isp. is present near the top of the layers. Vegetal remains, such as leaves are present.

Interpretation: FA3 reflects deposition by tractive unidirectional currents. The low abundance and low diversity of trace-fossil is attributed to a stressed expression of the *Skolithos* ichnofacies, indicating high-energy conditions in a brackish-water environment (Bann *et al*., 2008; Buatois and Mangano, 2011; MacEachern *et al*., 2005, 2007, 2010, 2012). The presence of vegetal remains and pebble-sized clasts reflect input from local rivers (Bhattacharya, 2006; Bann *et al*., 2008). FA3 is interpreted as mouth bar deposits (Enge *et al*., 2010) developed in a wave-dominated proximal delta front environment. Although no wave-generated structures were recorded in this FA, the effects of wave-processes are inferred because of the absence of a silty matrix within the sand which is associated with high frequency oscillatory motion of waves (Plint, 2010; Ainsworth *et al*., 2016) and because FA3 shows vertical association with the wave-dominated deposits of FA2.

Figure 7. Tabular beds of Facies Association 3 showing abundant unidirectional trough cross-bedded clean sandstones.

Facies Association 4: single-story distributary channels

Description: This FA erosionally overlies sediments of the wave-dominated distal delta front (FA2) or the wave-dominated proximal delta front (FA3) and it is overlain by FA2 deposits through flooding surfaces. FA4 consists of non-amalgamated lenticular sandbodies up to 6 m thick and 20 m wide (maximum) with erosional, concave-up base (Fig. 8a). These are composed of poorly-sorted, medium- to coarse-grained sandstones and pebbly-sandstones with fining-upward trends (Fig. 8b). FA4 shows abundant well-marked dune cross-bedded facies (Fig. 8c). Toward the top of these bodies, parallel-laminated and asymmetric ripple cross-laminated sandstones are common, and toward the base it shows a lag with mudstones rip-up and pebble-sized clasts (Fig. 8b, d). The paleocurrent directions measured on cross-beds are dominantly toward the southeast (Table 2). Although this FA is typically unburrowed (BI 0 - 1), it shows a scattered trace-fossil suite with *Ophiomorpha* isp., *Diplocraterion* isp., *Skolithos* isp. and lower proportions of *Palaeophycus* isp. and *Gordia* isp. Vegetal remains, such as leaves, wood fragments and carbonaceous material are abundant.

Interpretation: FA4 reflects deposition by tractive unidirectional currents. The erosional nature of the base, the fining-upward grain size trend, the presence of poorly sorted sediments, the unidirectional cross-beds, the lag at the base of some bodies and the abundant vegetal remains within these deposits indicate that FA4 was deposited in single-story fluvial distributary channels. The presence of a trace-fossil suite, attributed to a stressed expression of *Skolithos* ichnofacies (Beynon and Pemberton, 1992; Gibert and Martinell, 1993; MacEachern and Gingras, 2007; Bann *et al*., 2008; Buatois and Mángano, 2011; MacEachern *et al*., 2005, 2007, 2010, 2012) in some of these channels, indicates brackish-water conditions, suggesting marine influence in the most distal part of the channels (Bhattacharya, 2006; Fielding, 2010).

Facies Association 5: terminal distributary channels

Description: This FA is composed of amalgamated

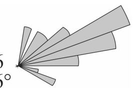
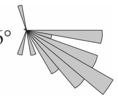
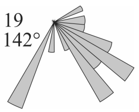
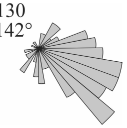
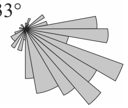
FA	LITHOLOGY	SEDIMENTARY STRUCTURES	SFs	PALEOCURRENTS	GEOMETRY	ICHNOLOGY	INTERPRETATION
FA1	Mudstones, heterolithic and very fine- to fine- grained sandstones, sparse pebble-sized clasts and abundant phytodetritus	Hummocky cross-bedding, organic drapes, parallel, flaser and wavy lamination, oscillation ripples, structureless	1, 3, 6, 8, 9, 11	-	Tabular	BI 0 - 3. Rh., Ar., Sk., Oph., Dp. isps. Stressed *Cruziana* ichnofacies	Wave-dominated prodelta
FA2	Muddy-sandstones to medium-grained sandstones. Abundant carbonaceous material, sparse pebble-sized clasts	Hummocky cross-bedding, parallel-lamination, structureless, soft-sediment deformation, mud rip-up clasts	3, 6, 9, 11, 12	-	Inclined tabular	BI 1 - 6. Oph., Th., Dp., Rh., Sk., Pl., Pa. isps. Stressed proximal *Cruziana* ichnofacies	Wave-dominated distal delta front
FA3	Well sorted fine- to medium-grained sandstones	Trough, tangential and planar cross-bedding, asymmetric ripple cross-lamination, parallel-lamination	4, 5, 7, 9	n = 26 mean = 66° 	Tabular	BI 0 - 2. Oph., Sk. isps. Stressed *Skolithos* ichnofacies	Wave-influenced mouth bars
FA4	Coarse-grained sandstones and pebbly sandstones. Abundant vegetal remains	Trough and tangential cross-bedding, organic drapes, parallel-lamination, asymmetric ripples, mud rip-up clasts, fining-upward	4, 5, 7, 9, 13	n = 19 mean = 126° 	Lenticular	BI 0 - 1. Oph., Sk., Dp., Go., Pa. isps. Stressed *Skolithos* ichnofacies	Single-story distributary channels
FA5	Pebbly-sandstones and fine-grained sandstones with sparse pebble-sized clasts. Abundant vegetal remains	Trough cross-bedding, structureless, organic drapes, mud rip-up clasts, fining-upward	4, 11, 13	n = 19 mean = 142° 	Tabular, lenticular	BI 1 - 6. Oph., Sk. isps. Stressed *Skolithos* ichnofacies	Terminal distributary channels
FA6	Poorly sorted muddy-sandstones and very fine- to fine-grained sandstones. Abundant vegetal fragments	Structureless, parallel-lamination, asymmetric ripple cross-lamination	7, 9, 11	-	Inclined tabular	BI 4 - 5. Oph., Pl., Pa., Te. isps. Stressed *Skolithos* ichnofacies	Fluvio-dominated distal delta front
FA7	Medium- to coarse-grained sandstones and pebbly-sandstones. Abundant leaves and wood fragments	Meter-scale trough and tangential cross-bedding, organic drapes, parallel-lamination, asymmetric ripple cross-lamination, mud rip-up clasts, soft-sediment deformation, coarsening-upward	4, 7, 9, 13	n = 130 mean = 142° 	High angle inclined cuneiform, lenticular	BI 0 - 2. Oph., Sk., Ar., Ro. isps. Stressed *Skolithos* ichnofacies	Fluvio-dominated mouth bars
FA8	Poorly sorted coarse-grained sandstones and pebbly-sandstones. Abundant leaves and wood fragments	Lateral accretion surfaces. Trough, tangential and planar cross-bedding, organic drapes, soft sediment deformation, parallel-lamination, asymmetric ripple cross-lamination	4, 5, 7, 9, 10, 11, 13	n = 169 mean = 133° 	Lenticular	BI 0 - 1. Oph., Sk., Ar. isps. Stressed Skolithos ichnofacies	High-sinuosity multi-story distributary channels
FA9	Organic-rich black mudstones, coal and very fine- to fine-grained sandstones	Parallel-lamination, structureless, peds, slickensides, trough cross-bedding	1, 2, 4, 9, 10	-	Tabular, lobular	BI 0 - 1. Pa., Te., Oph. isps. Rhiz.	Waterlogged interdistributary areas

Table 2. Summarized characteristics of the Facies Associations (FAs) identified for the La Anita Formation. Pl = *Planolites* isp., Pa = *Palaeophycus* isp., Rh = *Rhizocorallium* isp., Ar = *Arenicolites* isp., Sk = *Skolithos* isp., Oph = *Ophiomorpha* isp., Dp = *Diplocraterion* isp., Th = *Thallassinoides* isp., Go = *Gordia* isp., Ro = *Rosselia* isp., Te = *Teichichnus* isp. and Rhiz = rhizoliths; BI: Bioturbation Index.

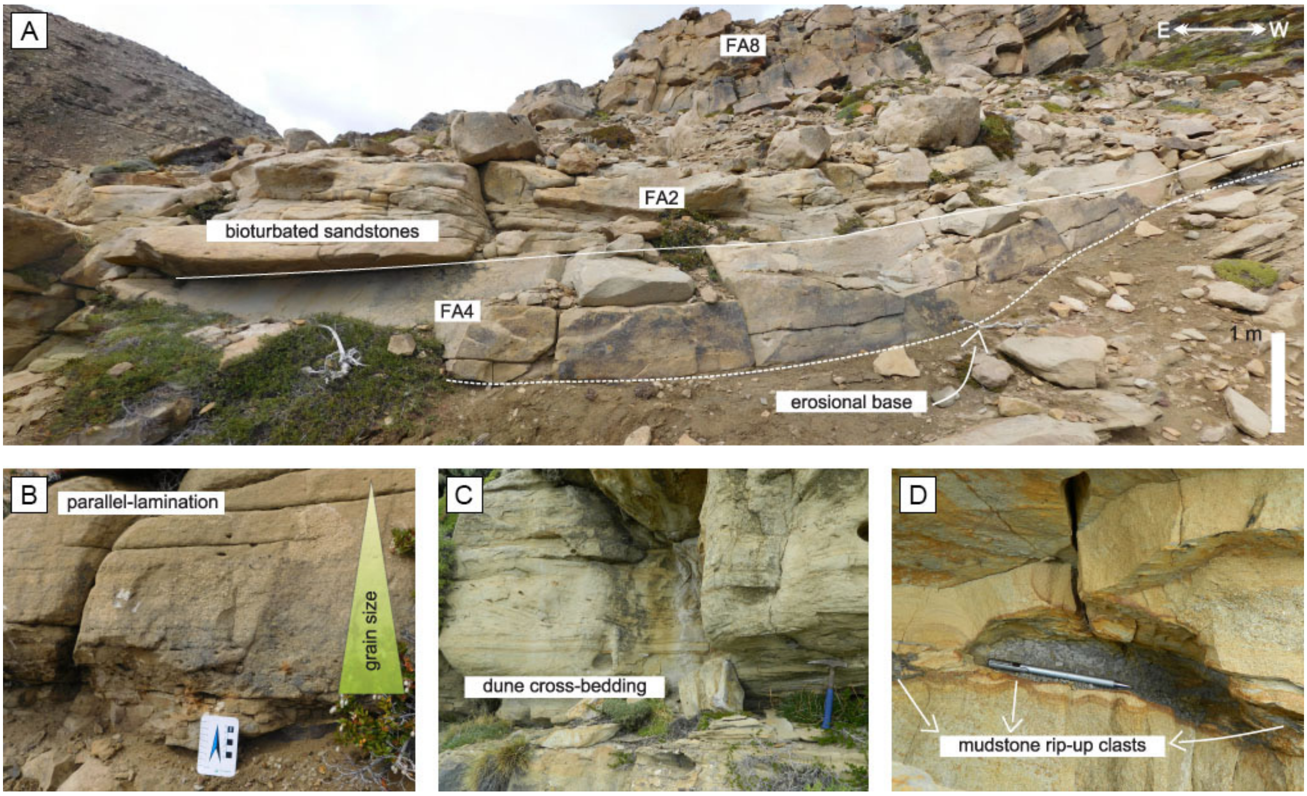


Figure 8. Representative outcrop photographs of Facies Association 4. **a)** Non-amalgamated channel-shaped body with concave-up, erosional base. **b)** Detail of the fining upward channel deposit with coarse-grained lag toward the base and parallel-laminated coarse-grained sandstones toward the top. **c)** Detail of trough and tangential cross-bedded sandstones facies. **d)** Coarse-grained mudstone rip-up clasts.

pebbly-sandstone bodies up to 7 m thick. They incise into sediments of wave-dominated distal delta front (FA2) and are overlain by single-story distributary channels (FA4). Individual bodies, or stories, are 1.5 m thick and few meters wide each and are composed of poorly-sorted pebbly-sandstones and fine-grained sandstones with fining-upward trends (Fig. 9). The erosional bases of the stories show coarse-grained lags followed by 3D cross-bedding facies that in turn grade upward to bioturbated sandstones (BI 1 - 6; Fig. 9). The paleocurrent directions determined from cross-beds are dominantly toward the south-east (Table 2). The trace-fossil suite consists of a monospecific assemblage of burrows with coated walls attributed to *Ophiomorpha* isp. with scattered simple vertical and horizontal burrows attributed to *Skolithos* isp. and *Palaeophycus* isp. Vegetal remains, such as leaves fragments and carbonaceous material are abundant.

Interpretation: FA5 reflects deposition by tractive unidirectional currents. The monospecific trace-fossil suite is attributed to a stressed expression of the *Skolithos* ichnofacies developed in a brackish to marine environment (Beynon and Pemberton, 1992; Gibert and Martinell, 1993; MacEachern and Gingras, 2007; Bann *et al*., 2008; Buatois and Mángano, 2011; MacEachern *et al*., 2005, 2007, 2010, 2012). The erosional nature of the base of these bodies, the presence of dune cross-bedded facies, the poorly-sorted character, the fining-upward grain-size trends, the upward increase of BI and the abundant vegetal fragments within this FA indicates deposition in terminal distributary channels (Olariu and Bhattacharya, 2006). The presence of distal delta front (FA2) and distributary channels (FA4) deposits below and above, respectively, supports the terminal distributary channel interpretation.

Facies Association 6: fluvio-dominated distal delta front

Description: This FA forms gently inclined (6° - 8°) tabular sandbodies (Fig. 10a) that dip toward the southeast and grade upward to coarser-grained sediments of fluvio-dominated mouth bars deposits (FA7; Fig. 10b). FA6 is composed of very fine- to fine-grained, poorly-sorted sandstones with abundant silty matrix. Primary sedimentary structures are obscured because of high bioturbation intensity (BI 4 - 5), however, parallel-laminated and small-scale trough cross-bedded and asymmetric ripple-laminated sandstones are observed. This FA shows low diversity but high abundance of biogenic structures. The trace-fossil suite is composed of burrows with coated walls attributed to *Ophiomorpha* isp., vertically stacked horizontal burrows attributed to *Teichichnus* isp., and simple horizontal burrows attributed to *Planolites* isp. and *Palaeophycus* isp. Vegetal remains, such as leaves, wood fragments and carbonaceous material are abundant.

Interpretation: The low diversity, but still high abundance of trace-fossils suggests accumulation in a low-energy and low-stress, brackish to marine environment associated with *Cruziana* ichnofacies. The presence of small-scale cross-bedding and parallel-lamination indicates deposition by unidirectional currents. The presence of abundant silty matrix and widespread vegetal remains suggest that these currents were fluvio-derived. Because of these features, FA6 is interpreted as the episodic deposition of turbidity currents in a fluvio-dominated distal delta front environment (Bhattacharya, 2006; Enge *et al*., 2010; Li *et al*., 2011; Kurcinka *et al*., 2018) that grades upward into fluvio-dominated mouth bars (FA7).

Facies Association 7: fluvio-dominated proximal delta front

Description: This FA commonly grades vertically from the sediments of the fluvio-dominated distal delta front (FA6) into poorly-sorted coarser-grained sandstones and pebbly sandstones (Figs. 10b). It is overlain by channelized incisions of high-sinuosity distributary channels (FA8) or by deposits of the interdistributary areas (FA9). FA7 consists of amalgamated high-angle (8° - 15°) sandy-clinothems up to 30 m thick and a few hundred meters wide that dips toward the southeast (Fig. 11a-c). Each clinothem is 5 – 7 m thick and composed of yellow-colored, medium- to coarse-grained sandstones and pebbly-sandstones with abundant silty matrix, showing both coarsening and fining upward trends. They show well-marked meter-scale cross-bedding structures (Fig. 11c-d) and subordinated parallel-laminated and ripple cross-laminated deposits. The paleocurrent directions measured from the cross-beds are mainly toward the southeast (Table 2). The lower portion of these bodies shows mudstones rip-up clasts and vegetal remains, such as leaves, wood fragments and carbonaceous material. Drapes of terrestrial phytodetritus are common in the cross-beds foresets. These drapes do not show a cyclic spacing distribution. This FA is typically unburrowed, however, sparse vertical burrows (BI 0 - 2) attributed to *Ophiomorpha* isp., *Skolithos* isp., *Arenicolites* isp. and *Rosselia* isp. appear mainly on top of some bodies.

Interpretation: FA7 reflects deposition by tractive unidirectional currents. Because of the high-angle clinothem geometry with forward-accretion of these beds (Fig. 11a-c), the unidirectional current-generated structures, the poor sorting, and the low BI, this FA is interpreted as mouth bar deposits, accumulated in a fluvio-dominated proximal delta front environment (Olariu *et al*., 2010; Enge *et al*., 2010; Kurcinka *et al*., 2018). This is also supported by the vertical association with the distal delta front and distributary channels, as well as the presence of a trace-fossil suite attributed a stressed expression of the *Skolithos* ichnofacies developed in a high-energy, brackish-water environment (Beynon and Pemberton, 1992; Gibert and Martinell, 1993; MacEachern and Gingras, 2007; Bann *et al*., 2008; Buatois and Mángano, 2011; MacEachern *et al*., 2005, 2007, 2010, 2012).

Facies Association 8: multi-story distributary channels

Description: This FA consists of amalgamated lenticular bodies 5 – 30 m thick with erosional, concave up base (Fig. 12a-b) that incises into the mouth bars of the fluvio-dominated proximal delta front (FA7). It also cuts down into sediments of FA2 and FA5 through a regional erosional surface. It occurs in vertical association with fine-grained interdistributary area deposits (FA9). Individual stories are up to 10 m thick and are separated by erosion surfaces, showing internal 2 m high and up to 30 m long inclined (20° - 35°) lateral accretion surfaces (Fig. 12b) that

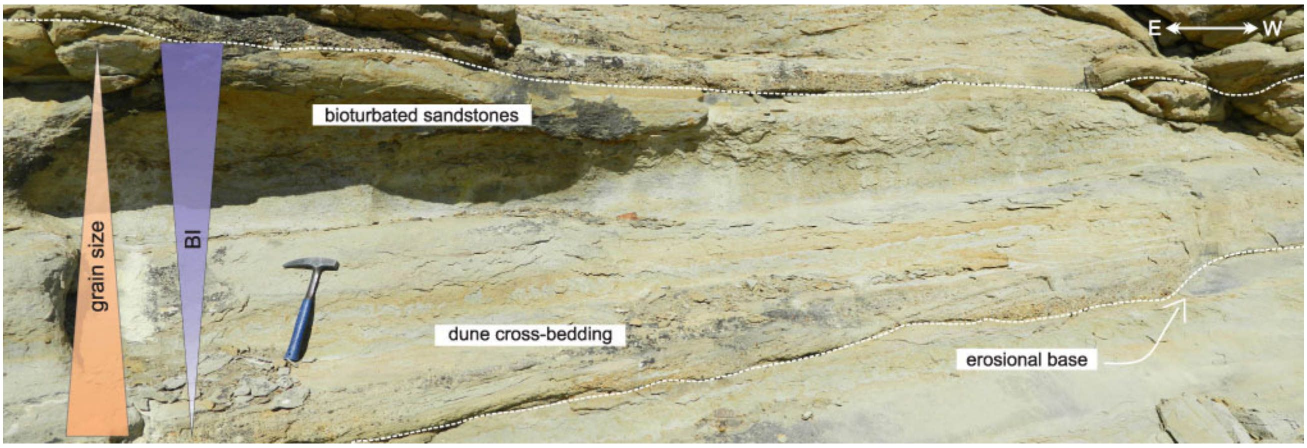


Figure 9. Detail of Facies Association 5 showing amalgamated, erosionally based bodies, with fining-upward trend. The trough cross-beds at the base of these stories are obscured upward due to the gradual increase in the bioturbation index (BI 1 - 6).

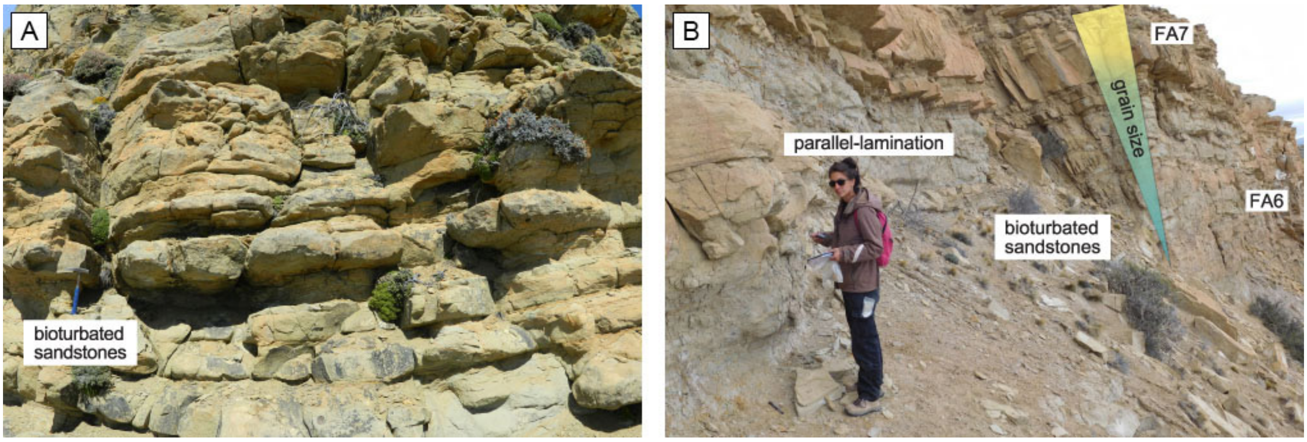


Figure 10. Representative outcrop photographs of Facies Association 6. **a)** Detail of the gently inclined bioturbated tabular sandbodies. **b)** Detail showing the poorly-sorted, highly bioturbated sandstones (BI 4-5), with local parallel-lamination that coarsens upward into sandstones of Facies Association 7.

dip toward the northeast and southwest. These stories are filled with poorly-sorted coarse-grained sandstones and pebbly-sandstones. They show 3D dune cross-bedded facies and fining-upward trends (Fig. 12c-d). Soft-sediment deformation structures, parallel-laminated and ripple cross-laminated sandstones, as well as structureless conglomerates deposits are also present. Erosional bases of stories are covered by a lag with pebble-sized clasts and mudstone rip-up clasts together with abundant vegetal remains, such as leaves and wood fragments. Organic phytodetritus drapes are present in the foreset and toeset of cross-beds showing noncyclical spacing on their distribution (Fig. 12d). Cross-beds are oriented mainly toward the southeast (Table 2). This FA is typically unburrowed, however, a sparse trace-fossil suite (BI 0 - 1) composed of vertical *Ophiomorpha* isp., *Skolithos* isp. and *Arenicolites* isp. burrows is present.

Interpretation: This FA reflects deposition by high-energy tractive unidirectional currents. The internal lateral accretion surfaces indicate high-sinuosity of these currents. Based on the erosional nature of the bodies base, the poor sorting of their infill, the fining upward grain size trend, the current-generated structures, the lag at the base of some bodies and the abundant vegetal remains evidences, this FA is interpreted as high-sinuosity meandering distributary channels within a delta plain environment (Bhattacharya, 2006; Olariu and Bhattacharya, 2006). The presence of a marine

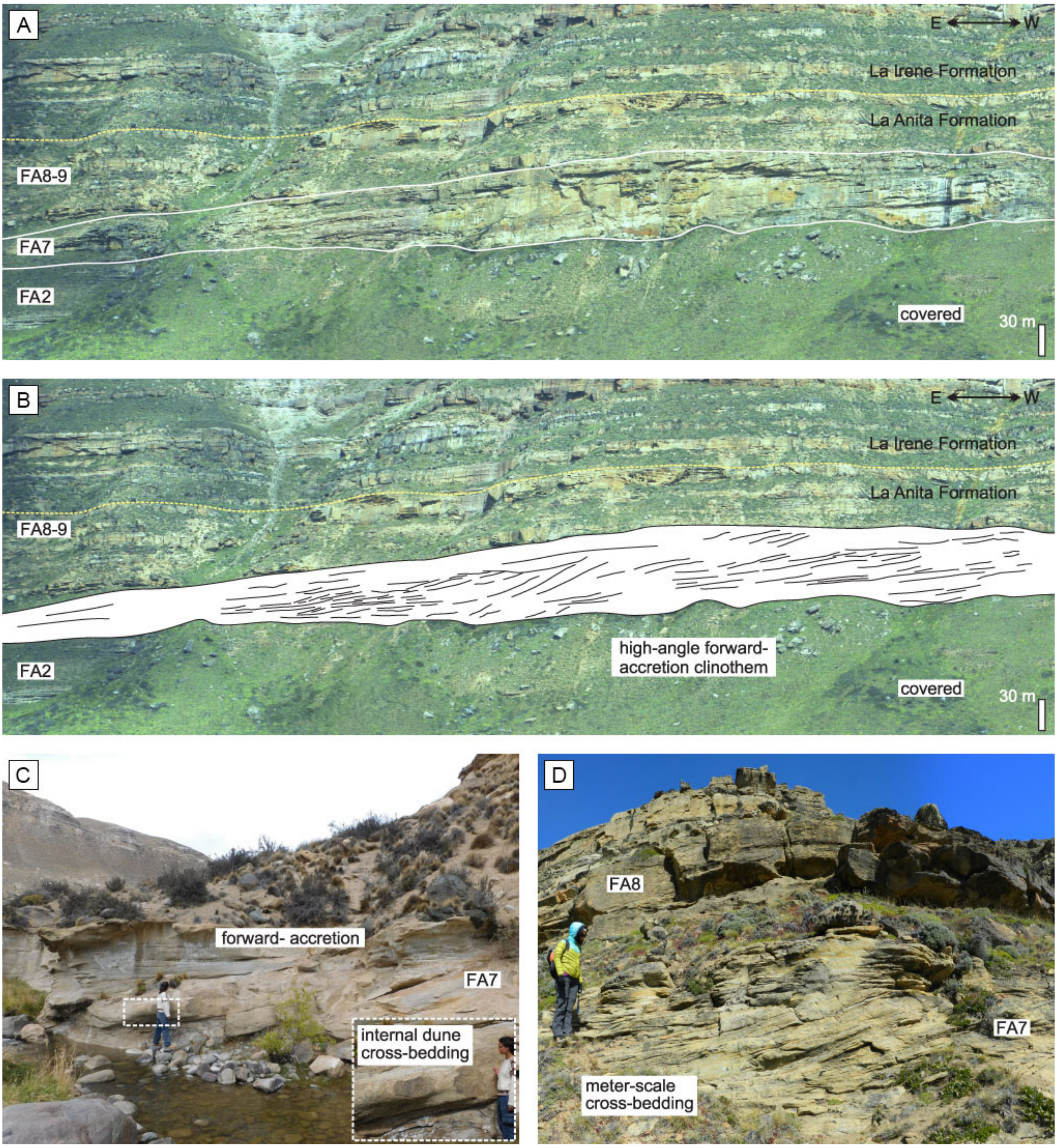


Figure 11. Representative outcrop photographs of Facies Association 7. **a)** and **b)** Outcrop panels showing high-angle forward-accretion clinothems dipping toward the southeast. **c)** Detail of the forward-accretion climothems. The inset in Fig. 11c shows detail of internal dune cross-bedding dipping in the same direction as the clinothems. **d)** Detail of internal large-scale dune cross-bedding.

trace-fossil suite attributed to a stressed expression of *Skolithos* ichnofacies (Beynon and Pemberton, 1992; Gibert and Martinell, 1993; MacEachern and Gingras, 2007; Bhattacharya, 2006; Buatois and Mangano, 2011; MacEachern *et al*., 2005, 2007, 2010, 2012) in some channels indicates brackish-water conditions (Bhattacharya, 2006; Fielding, 2010). The lateral and vertical complexity of channel bodies indicate that their infill was multi-story. The close association with the interdistributary areas deposits

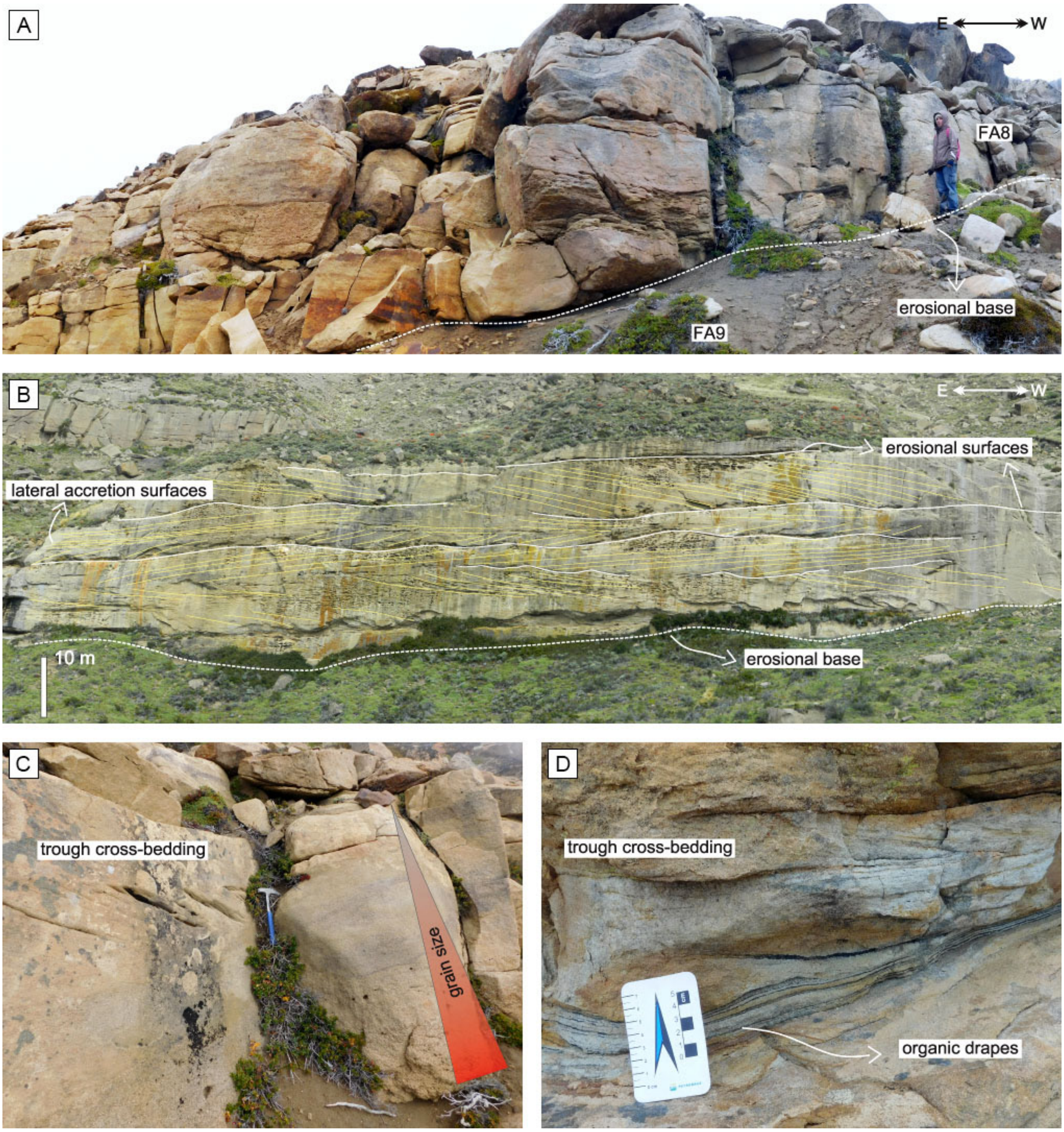


Figure 12. Representative outcrop photographs of Facies Association 8. **a)** Detail of channel-shaped body with concave-up, erosional base. **b)** Photopanel showing lenticular amalgamated stories with internal lateral accretion surfaces and bounded by high hierarchy erosional surfaces. **c)** Details of fining upward trends and trough cross-bedded facies. **d)** Organic matter drapes on cross-beds toesets with noncyclical spacing.

(FA9) supports this interpretation.

Facies Association 9: interdistributary areas

Description: This FA is in vertical association with multi-story distributary channels of FA8 and consists of tabular bodies with thicknesses that range from 1 to 17 meters. It is composed of organic-rich black mudstones to clean coal, siltstones and subordinate very fine-grained sandstones (Fig. 13a). They show parallel-laminated or structureless mudstones deposits with pedogenic features such as slickensides, both angular and subangular blocky peds, and abundant rhizoliths. The BI is low (0 – 1) with horizontal simple burrows attributed to *Planolites* isp. as the dominant trace, but sandstone layers are occasionally intensely bioturbated (BI 4 – 5) with horizontal burrows of *Planolites* isp. and *Teichichnus* isp. as the identified traces. In addition to carbonaceous material, wood fragments are common. These fine-grained layers are eventually interrupted by lenticular bodies of fine-grained sandstones with sharp bases and convex-up tops (Fig. 13b) with trough cross-bedded and parallel-laminated facies and sparse vertical burrows attributed to *Ophiomorpha* isp.

Interpretation: Fine-grained deposits suggest low-energy conditions during the accumulation of the FA9. It is interpreted to have been deposited in waterlogged, swamp-like interdistributary areas filled by overbank spilling of fine-grained material from distributary fluvial channels (AF8) during flood stages (Bhattacharya, 2006; Fielding, 2010). The lobular sandbodies with tractive structures reflect deposition by unidirectional tractive currents and are interpreted as crevasse-splays deposits (Mjøs *et al.*, 1993; Perez-Arlucea and Smith, 1999). The pedogenic features and the presence of abundant poorly-decomposed organic matter suggest soil development in a waterlogged environment with reductive conditions (Everett, 1983; Retallack, 2001). The presence of marine traces indicates that brackish-water conditions were established occasionally in these interdistributary areas (Gugliotta *et al.*, 2015).

DISCUSSION

Stratigraphic architecture and distribution of facies associations

The LAF deposits can be differentiated into two units, here defined as upper unit and lower unit. This differentiation is based on their color difference and the presence of a regional low-angle erosion surface bounding them that incise ~ 50 m into the underlying lower unit (Figs. 4, 14). In addition, this stratigraphic differentiation coincides with the vertical variations in the relative roles of depositional processes and spatial distribution of FAs (Figs. 4, 15) which are further discussed below.

The FAs of the LAF evidence both marine and fluvial processes being active in different proportions during its accumulation. In this contribution we followed the ideas proposed by Ainsworth *et al.* (2008) who set up criteria for defining process dominance and influence within facies associations in mixed-process coastal systems. The most common sedimentary structures define the dominant depositional process within a FA, and secondary processes which lead to the generation of subordinate features are said to have influenced deposition. The dominant and subordinate processes that constitute the largest proportion of a stratigraphic unit are considered to represent the dominant and subordinate processes that were active in the stratigraphic unit (*cf.* Ainsworth *et al.*, 2008, 2011).

Lower unit

This unit coarsens upward and grades from fine-grained slope deposits of the Alta Vista Formation (Malkowski *et al.*, 2017) into a dominantly sandy, gray-colored succession. Its upper boundary is a regional erosion surface which in turn is followed by the upper unit deposits of the LAF (Figs. 4, 14, 15). The vertical stacking pattern of the FAs of the lower unit is mainly aggradational to progradational, although the coarsening-upward grain size trends suggests a progradational depositional system (Figs. 4, 15).

The abundance of HCS and other wave-generated structures, such as parallel-lamination and wavy-lamination all along prodelta and distal delta front deposits of FA1 and FA2, respectively, suggests deposition under strong influence of fair weather wave- and storm-processes. However, fluvial-current effects are also recognized in these FAs in the form of pebble-sized clasts and abundant land-driven vegetal remains. The trace-fossil suites indicate high-energy conditions associated with the high recurrence of storm events. In parallel, the low abundance and diversity of traces, especially those found on fair-weather beds of FA1, could also be responding to stressing conditions produced by low salinity and bottom oxygenation, associated with fluvial-discharge effects in the coastal area.

Mouth bar deposits of FA3 are poorly represented in the lower unit. They grade from wave- and storm-generated layers of FA2 into well-sorted sandstones, and are overlain by channel incisions (FA4) or by

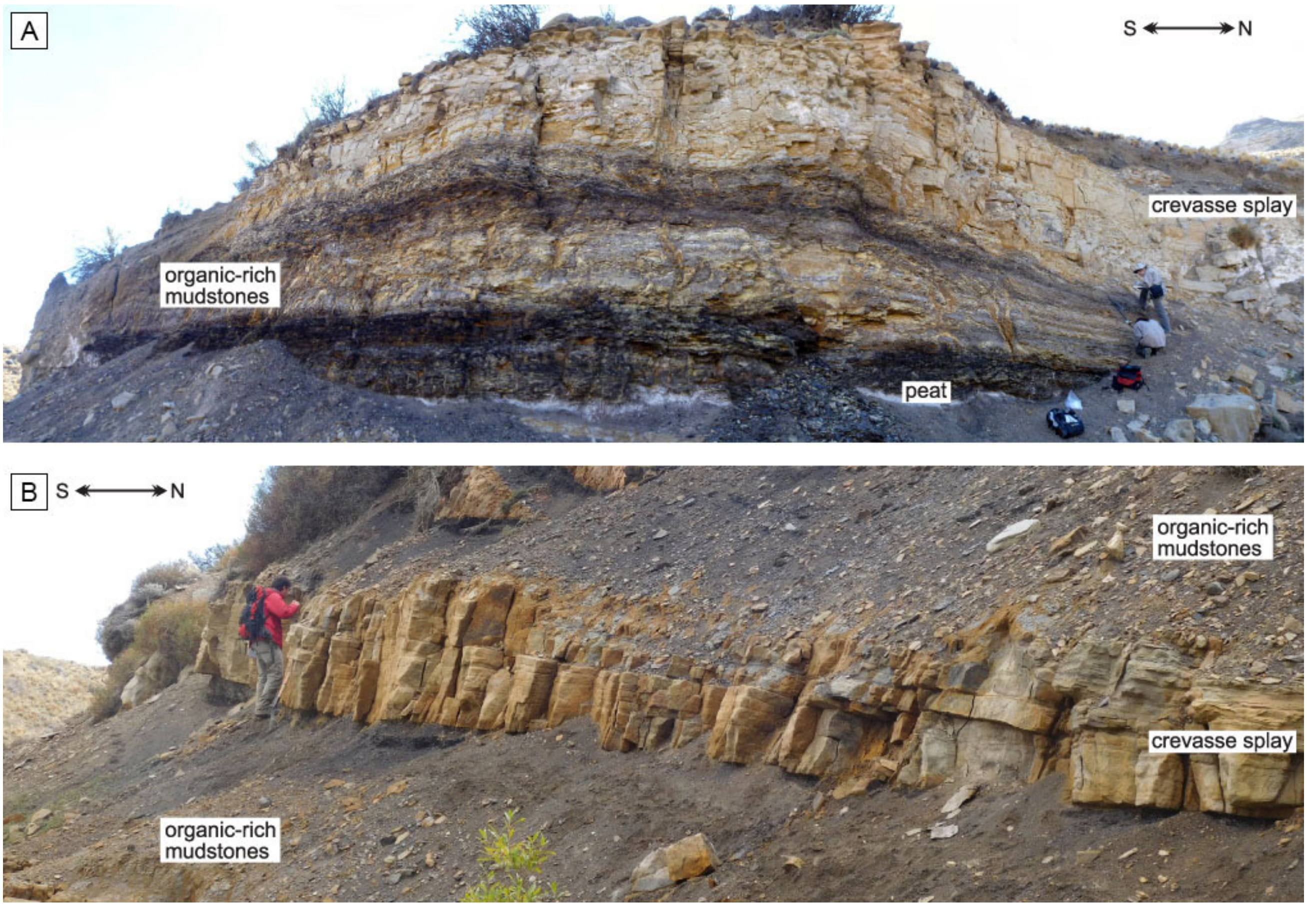


Figure 13. Representative outcrop photographs of Facies Association 9, **a)** Panel showing tabular clean coal to organic-rich mudstones deposits. **b)** Detail of trough cross-bedded convex-up lenticular body interpreted as crevasse splay deposits, interbedded with organic-rich mudstones.

wave-dominated distal delta front deposits (FA2). Mouth bar deposits develop when a turbulent current expands from the mouth of a distributary channel into a standing body of water (Wright, 1977). Mouth bars are, by definition, generated by fluvial processes. However, the recognition of a wave-dominated distal delta front under and above these mouth bar deposits, together with the lack of a silty matrix, suggest that they were developed in a wave-dominated context. The scarce proportion of mouth bar deposits in the lower unit (Fig. 15) could be related to the high recurrence of storm events, evidenced in the prodelta and distal delta front deposits, because during storms, high amounts of sand are stripped from shallow-water zones and transported seaward (Dumas and Arnott, 2006).

Cross-bedded structures from distributary and terminal distributary channel deposits of FAs 4 and 5 show mean paleocurrent directions toward the southeast (Fig. 15; Table 2), however, terminal distributary channels cross-beds orientation show greater dispersion in the measured data than the channels of FA4 were the dispersion is considerably minor (Table 2). Cross-beds orientation from mouth bars (FA3) are oblique, almost orthogonal, to both distributary and terminal distributary channels mean paleoflow (Fig. 15; Table 2). This oblique flow relationship suggests an oblique wave-approaching to the shoreline and this may again reflects wave influence on mouth bars (Ainsworth *et al*., 2016).

The progradational depositional system of the lower unit of the LAF is interpreted as wave-dominated, fluvial-influenced delta system (*cf*. Ainsworth *et al*., 2008, 2011; Fig. 16a). Even though the delta was fed by distributary fluvial channels, the distribution of the sediment was dominated by the action of waves. Storm and wave effects

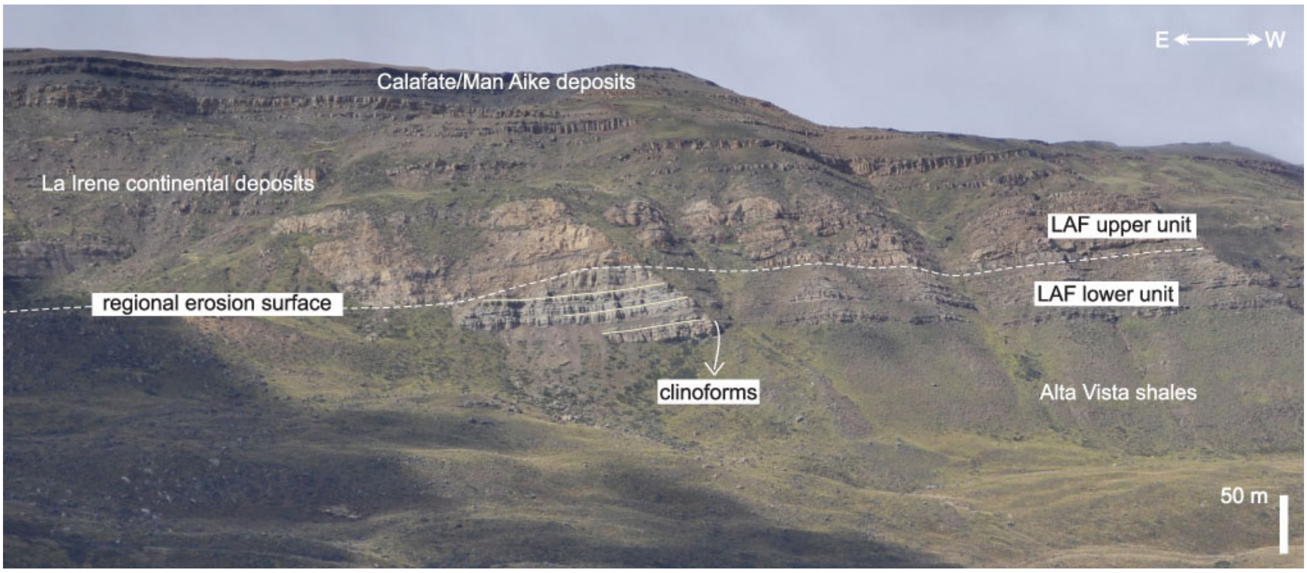


Figure 14. Outcrop photograph of the cliff at the Anita farm with a view to the south, showing the stratigraphic distribution of the Upper Cretaceous – Paleocene deposits of the AMB. The LAF lower unit shows gray-colored strata and low-angle clinoforms dipping toward the southeast. The upper unit of the LAF shows yellow-colored strata. The upper and lower units of the LAF are bounded by a regional erosional surface.

are strongly represented in the sediments of the prodelta (FA1) distal delta front (FA2) and mouth bars (FA3; Figs. 4, 15; Table 2). Although fluvial-currents do not appear as a dominating process during the deposition of the lower unit, it is present in all FAs as subordinate features (Figs. 4, 15). These fluvial-influenced features within the lower unit deposits are a key element to differentiate between wave-dominated deltas and nonfluvialite wave-dominated shoreface-shelf depositional systems (*sensu* Ainsworth *et al*., 2011). The oblique wave-approaching to the coastline produces mouth bars deflection and migration in a shore-parallel direction for several kilometers (Bhattacharya *et al.,* 2010), passing gradationally into attached beach ridge and/or coexisting shoreface deposits (Rodriguez *et al*., 2000; Bhattacharya and Giosan, 2003; Sømme *et al*., 2008; Bhattacharya, 2010; Ainsworth *et al*., 2019; Fig. 16a). Paleocurrent directions of the lower unit indicate that progradation of the system was toward the southeast (Table 2; Figs. 15, 16a). This is further supported by the presence of clinoform dipping surfaces toward the same direction (Fig. 14).

Upper unit

The base of this unit coincides with the regional erosion surface dividing the two units defined in this work (Figs. 4, 14, 15). The upper unit shows no lateral nor vertical gradations with the underlying lower unit and it is overlain by the Upper Cretaceous Continental Deposits (*sensu* Tettamanti *et al*., this volume) of the La Irene or Cerro Fortaleza formations, representing a progressive continentalization of the basin. The upper unit is yellow-colored and shows coarser grain size than the lower unit (Figs. 4, 14). The vertical stacking pattern of FAs suggests deposition by a progradational depositional system (Fig. 15).

Multi-story distributary channels (FA8) are found in the lower portion of the unit, above the regional erosional surface, as well as in the upper portion of this unit, in this case associated with fine-grained deposits of the interdistributary areas (FA9; Fig. 15). Deposition within these channels do not record any influence of marine-processes (*i.e*. waves nor tides).

Distal delta front and mouth bar sediments of the upper unit of the LAF differ considerably from those present in the lower unit. The distal delta front (FA6) is associated with a low-energy brackish-water environment. The presence of silty matrix and parallel-laminated, asymmetric-ripples and cross-bedded facies suggest deposition by unidirectional fluvial-currents with no evidence of wave or tidal influence. FA6 grades vertically and laterally into coarser-grained mouth bar deposits (FA7). These

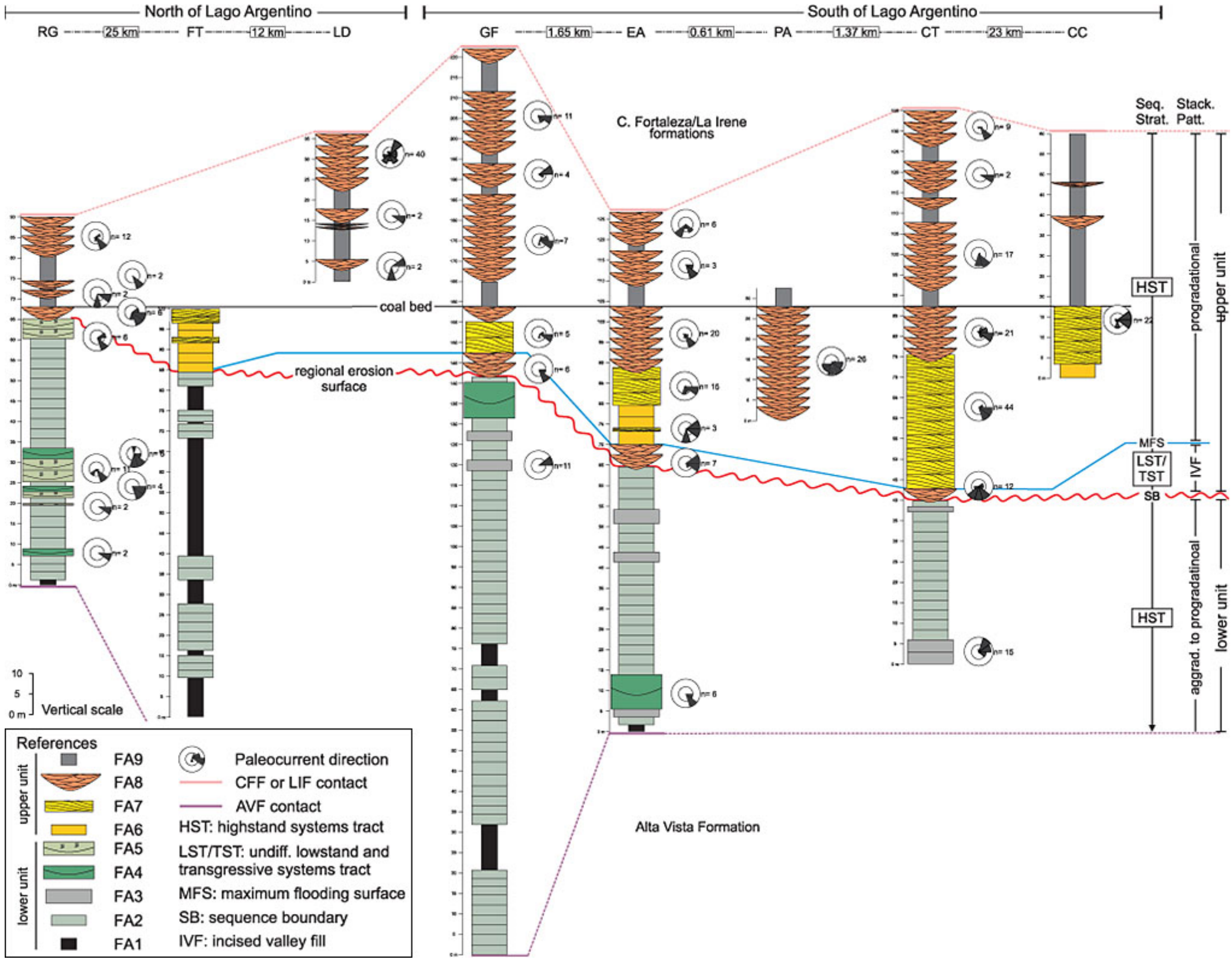


Figure 15. Correlation panel showing vertical stacking patterns and lateral distribution of Facies Associations (FAs) together with the sequence stratigraphic framework for the La Anita Formation. The maximum flooding surface (MFS) and the first clean coal bed had been walked and used as correlation datum. AVF = Alta Vista Formation; CCF = Cerro Fortaleza Formation; LIF = La Irene Formation.

mouth bar deposits differ from the lower unit ones because they are clearly poorly-sorted, with abundant silty matrix; are coarser-grained and form amalgamated high-angle dipping clinothems. No wave, or tidal effects were recorded in mouth bars of FA7 suggesting that deposition was dominated by fluvial-processes.

The upper unit of the LAF evidence deposition dominated by fluvial processes in a stressed brackish-water environment. This progradational, coarsening-upward system is interpreted as a fluvio-dominated delta (Ainsworth *et al*., 2008; 2011; Fig. 16b). Mouth bars and distributary channels show a wide range of paleocurrent directions (Figs. 15, 16b; Table 2), as expected in a fluvio-dominated delta. However, the progradation of the system was, as in the lower section, toward the southeast (Fig. 16b).

Sequence stratigraphic implications

The two units of the LAF could be attributed as part of the same depositional sequence, where both would represent coexisting lateral active lobes of an asymmetrical-delta (Bhattacharya and Giosan, 2003). Alternatively, they can be considered as two different depositional sequences. In the first case both units should be genetically related, representing temporal variations in shoreline trajectory and paleogeography, and they should show oblique direction of progradation as suggested by Charvin *et al*. (2010). However, our data suggest that both units of the LAF are genetically unrelated because: i) no

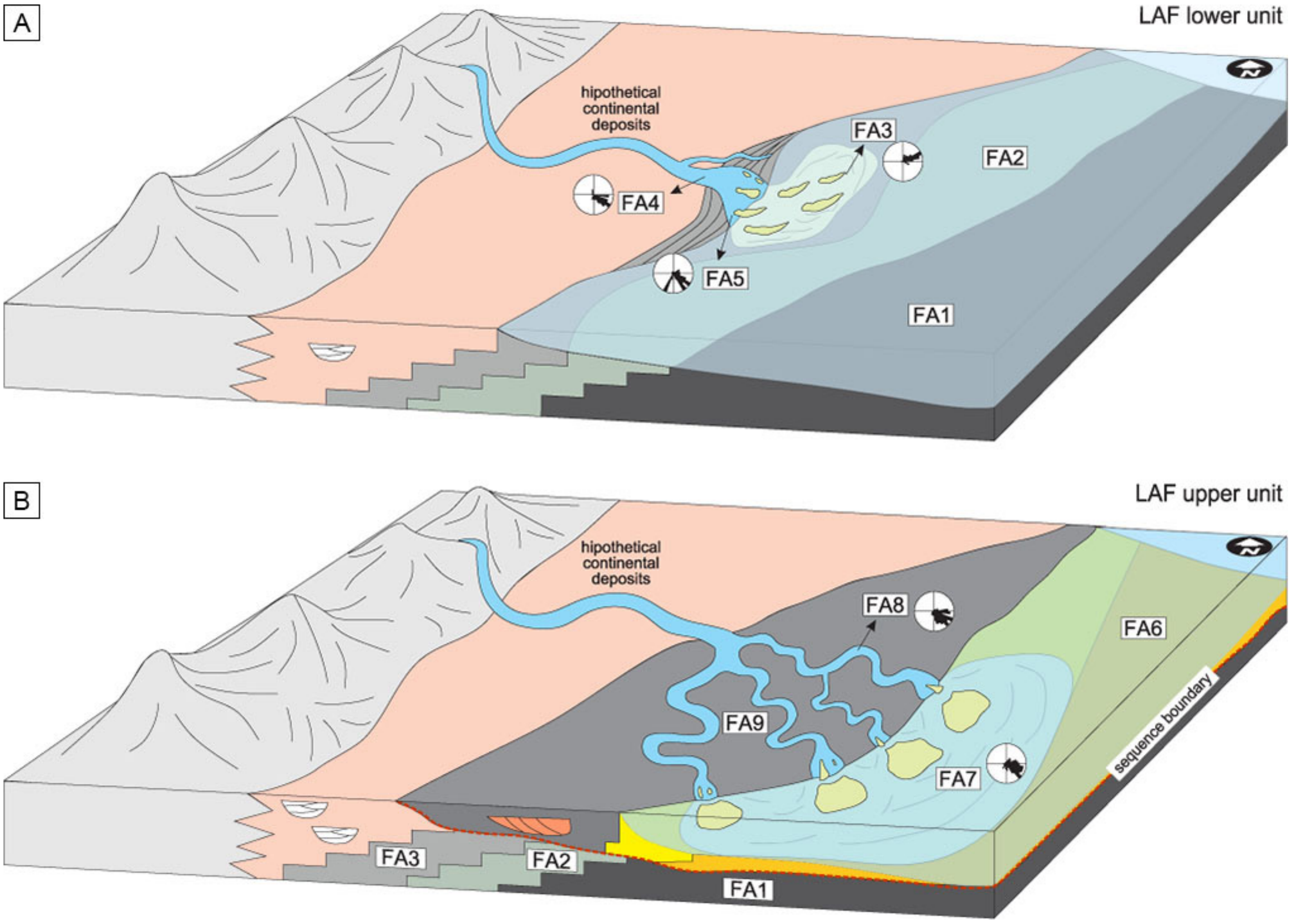


Figure 16. Paleoenvironmental and paleogeographic reconstruction for the La Anita Formation deposits. **a)** Lower unit and **b)** upper unit. Rose-diagrams show paleocurrent directions of each Facies Association (FA).

lateral relationship in FAs distribution was recorded between them, ii) both show the same southeastward direction of progradation that suggests the same direction in shoreline trajectory, and iii) they present a regional erosion surface bounding them.

This erosion surface consists of a low-relief regional incision that cuts down ~ 100 m into the underlying wave-dominated fluvial-influenced delta system of the lower unit (Figs. 14-16). This surface is immediately overlain by the coarsest grained, laterally and vertically amalgamated multi-story channel deposits (FA8) of the upper unit. The multi-story, multi-lateral nature of these channels could represent the fill of coastal incised valleys (Fielding, 2010), associated to a sequence boundary triggered by a relative sea-level fall (Catuneanu, 2006; Catuneanu *et al.*, 2009; Figs. 15, 16).

In turn, the lower unit of the LAF grades from the deep-marine, slope black shale deposits of the Alta Vista Formation (Malkowski *et al.*, 2017). The lower unit is interpreted as the highstand systems tract (HST), indicated by the aggradational to progradational vertical stacking pattern of its FAs and by its location immediately below the interpreted sequence boundary (Catuneanu, 2006; Catuneanu *et al.*, 2009; Fig. 15). The upper unit of the LAF shows evidence a complete relative sea-level cycle. The lowest interval of the upper unit is represented by incised valley fill deposits and it is interpreted as an undifferentiated lowstand and transgressive systems tracts (LST-TST; Fig. 15). It is not possible to distinguish between the LST and the TST because of the lack of lateral gradation to distal deposits (Catuneanu, 2006; Kurcinka *et al.*, 2018). The top of the LST-TST is marked at the base of the fluvio-dominated delta front (FAs 6 and 7), interpreted as the maximum flooding surface (MFS; Catuneanu, 2006; Catuneanu *et al.*, 2009; Fig. 15). The expression of the MFS is progressively lost toward the north of the study area (Fig. 15). The deposits above the LST-TST are represented by the fluvio-dominated delta front (FAs 6 and 7) and delta plain (FAs 8 and 9) deposits, with a strongly progradational stacking pattern. For this reason, the latter are interpreted as the HST (Catuneanu, 2006, Catuneanu *et al*., 2009; Kurcinka *et al*., 2018; Fig 15).

CONCLUSIONS

This study highlights the importance of depositional process-based facies analysis for interpreting coastal depositional systems in order to determinate the role of wave, tidal and/or fluvial processes during deposition. The La Anita Formation is interpreted as a deltaic depositional system, which shows vertical variations in the relative roles of wave and fluvial processes. This allowed to differentiate the La Anita Formation deposits into a wave-dominated lower unit and a fluvio-dominated upper unit, each representing different depositional sequences.

The lower unit of the La Anita Formation is interpreted as a wave-dominated fluvial-influenced delta system, based on the presence of wave-generated structures, coarsening-upward trends and aggradational to progradational vertical stacking patters. Wave-processes controlled the deposition on the prodelta and the distal delta front. Also the oblique wave-approach to the coastline elongated mouth bars deposits in a shore-parallel direction. This wave-dominated, fluvial-influenced delta is interpreted as part of a HST located under the interpreted sequence boundary.

The upper unit and the lower unit are bounded by a regional erosion surface which is interpreted as a sequence boundary related to a relative sea-level fall. This explains why there is no evidence of vertical nor lateral gradation between the lower and the upper units.

The upper unit of the La Anita Formation has been interpreted as a fluvio-dominated delta system, with abundant unidirectional current-generated structures, coarsening-upward trend, and overall progradational vertical stacking pattern of its facies associations. This unit does not record any wave nor tidal effects and its deposits reflect a complete relative sea-level cycle. The lowermost channelized deposits represent incised valley fills related with the sequence boundary and are interpreted as the undifferentiated LST-TST which is covered by the HST through the maximum flooding surface.

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